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EVALUATION OF THE EFFECT OF CRACK CLOSURE ON FATIGUE CRACK GROWTH OF SIMULATED SHORT CRACKS

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SUMMARY

A test program was performed to determine the influence of crack closure on fatigue crack growth (FCG) rates of short cracks. By use of the standard compact tension specimen, test procedures were devised to evaluate closure loads in the wake of the crack behind its tip. The first procedure determined the magnitude of crack closure as a function of the fatigued crack wake by incrementally removing the contacting wake surfaces and measuring closure load at each increment. The second procedure used a low-high loading sequence to simulate short crack behavior. Based on the results, it was concluded that crack closure is not the major reason for the more rapid growth of short cracks as compared to long crack growth.

INTRODUCTION

Considerable effort has been made recently to explain the fatigue crack growth behavior of short cracks. It has been recognized (ref. 1) that the growth rates of short cracks do not conform with predictions made on the basis of linear elastic fracture mechanics (LEFM) and long crack behavior.

Two hypotheses have been postulated to account for accelerated growth of short cracks. Some investigators (refs. 2 to 4) have questioned the validity of the use of LEFM parameters to describe short crack FCG behavior; instead they proposed the use of the J-integral concept and an empirical length parameter to correlate short and long crack growth rates. Another explanation for the difference in short and long crack behavior is based on the influence of crack closure on fatigue crack growth. This influence was first proposed by Broek (ref. 5) and has been supported recently by others (refs. 6 to 8).

The purpose of this investigation was to evaluate the influence of crack closure on fatigue crack growth of short cracks. The driving force for fatigue crack growth is usually taken to be the stress intensity range (ΔK).

With

$$\Delta K = K_{max} - K_{min} \tag{1}$$

where K_{max} and K_{min} are respectively the maximum and minimum stress intensities applied in fatigue cycling. However, Elber (ref. 9) noted that crack surfaces can be closed over a considerable portion of the load cycle.

He proposed that the driving force for crack growth is an effective stress intensity range (ΔK_{eff}) defined as:

$$\Delta K_{eff} = K_{max} - K_{CL} \tag{2}$$

where K_{CL} is the highest stress intensity at which the crack tip is closed. In addition to Elber's plasticity induced closure, other closure mechanisms such as roughness and oxide induced closure have been shown to occur (refs. 10 to 11).

It has been hypothesized (refs. 6 to 8) that closure stress increases with the increasing wake of the crack, and since short cracks have limited wakes, the amount of closure of these cracks is severely limited. Compared to large cracks, the lower closure level of small cracks gives a larger ΔK_{eff}. The larger ΔK_{eff} produces the more rapid FCG observed in small cracks.

One of the main problems in evaluating published material on short cracks is the use of a large variety of specimen configurations which do not appear to have established stress intensity calibrations. In order to overcome this problem, a test program was designed to evaluate the effects of crack closure on short crack behavior by simulating short crack conditions with standard compact tension specimens, where the stress intensity calibration is well defined. Two types of tests were performed to simulate the short crack closure behavior. Both of them dealt with the reduction of closure stresses in the crack wake behind the crack tip and are fully described later in the paper.

PROCEDURE

All specimens were machined from a 3.2 mm (0.125 in) thick sheet of 7075-T6 aluminum with tensile properties as detailed in table I. For the FCG studies, compact tension (CT) specimens were used. The width of the CT specimens was 38.1 mm (1.5 in), the initial a/w ratio was 0.2, and the thickness was that of the as received sheet. All tests were performed using a closed loop servohydraulic fatigue machine. The testing was done at an R ratio of 0.1 in an ambient air environment. All testing was computer controlled using a compliance technique to maintain a constant stress intensity and to determine crack length. Occasional optical readings were taken to confirm the compliance readings of the crack length.

Two types of tests were performed to simulate short crack behavior. The first consisted of precracking the CT specimen at a ΔK of 8.8 MPa $\sqrt{m}$ (8 ksi $\sqrt{in}$) until an a/w of 0.47 was reached. Using a jewelers saw, increments of the fatigued crack wake behind the crack tip were removed. After each increment of the crack wake was cut out, several load-displacement curves were obtained, from which closure loads were determined. The closure load was taken to be the first deviation from linearity in the unloading portion of the load-displacement curve. The removal of the crack wake continued until only a 0.05 mm (0.002 in) segment of the fatigued crack wake behind the crack tip was left.

The second test conducted to simulate short crack behavior consisted of precracking duplicate specimens at a ΔK of 4.4 MPa $\sqrt{m}$ (4 ksi $\sqrt{in}$) until an

a/w ratio of 0.35 was achieved. The stress intensity was then increased to a ΔK of 13.4 MPa $\sqrt{m}$ (12.2 ksi $\sqrt{in}$) under which the specimens were fatigued until failure. FCG rates immediately after the transition to the higher stress intensity were compared to the rates obtained after the crack had propagated away from the transition. In order to confirm the results, fractographic analysis of the striation spacings was performed using a scanning electron microscope. All fractographs were taken using a 0° tilt to limit the possible distortions of striation spacings.

RESULTS AND DISCUSSION

The limited wakes of short cracks have been suggested (refs. 6 to 8) as decreasing the closure stress and increasing FCG rates. The first test described in the procedure was devised to simulate this behavior by incrementally removing the wake of the crack. Closure loads were determined after removal of each crack wake increment. The distance of the remaining wake behind the crack tip ranged from 2.5 mm (0.100 in) to 0.05 mm (0.002 in). The results are shown in figure 1. There appeared to be no change of the closure level with the removal of the crack wake. However, the accuracy of the 0.05 mm (0.002 in) reading is doubtful since it was difficult to pick an accurate estimate of the closure load for such a small crack wake. Thus, it can only be concluded from the above test that the closure stress and the resulting ΔK_{eff} does not change for cracks having fatigue crack wakes greater than 0.125 mm (0.005 in).

The second test described in the procedure was performed to evaluate closure behavior for cracks with wakes shorter than 0.125 mm (0.005 in). The following paragraph explains the rationale of the test.

The crack closure hypothesis for the more rapid FCG in short cracks compared to long cracks at equal applied ΔK, relates to the length of the crack wake. The small wake of a short crack produces smaller closure loads in comparison to a longer crack wake. A larger ΔK_{eff} therefore occurs in the short crack specimen and subsequently greater FCG rates result. Short crack behavior in a long crack fatigue specimen should be simulated when the applied ΔK is increased from low to high. Crack closure increases with applied stress intensity. A transition from low to a high enough stress intensity should result in closure after the transition being increased to a point where the crack closure at lower ΔK can be neglected. Subsequent crack growth can then be assumed to be effected only by the crack closure developing from the point of stress intensity transition. Thus, if the closure hypothesis is correct, after the transition the FCG rate should be initially higher and then progressively decrease due to the growing crack wake until full closure stresses for the higher stress intensity are developed.

The results of the experiment are plotted in figure 2. No initial higher crack growth rate was detected after the transition to higher stress intensity. The crack growth rate for the first 0.125 mm (0.005 in) of crack growth after the transition into the high stress intensity region is essentially equal to the growth rates for longer cracks at the same stress intensity. To confirm these results a fractographic evaluation of the striation spacings after the transition into the high ΔK region was performed. The results of

the fractographic evaluation are shown in figures 3 and 4. As seen in figure 4 after the transition, there is no observable change in FCG rates as function of crack length.

Review of the literature reveals some controversy regarding the FCG rates when a low-high loading sequence is applied. The results of Hardrath and co-workers (refs. 12 and 13) agree with results obtained in the present study in that no initial increase in FCG rate was found after the transition to higher stress intensity. vonEuw, et al. (ref. 4) however, have noted an initial increase at the second stress level. They also documented this increase by evaluating striation spacing. However, in their study they found large discrepancies (up to 61 percent) between the FCG rates obtained from striation measurement and the macroscopic data. In the present study, the largest discrepancy between the FCG rates as measured by both techniques was less than 14 percent. Striation measurements consistently showed slightly lower growth rates possibly due to a small tilt of the fracture features with the respect to the screen projection. Some tilt is unavoidable although care was taken to minimize it. The excellent agreement between the two measuring techniques gives added confidence to the data obtained in this study.

Both types of tests performed in this study indicate that crack closure behavior is not the major cause for the greater growth rate of short cracks as compared to long cracks. The following hypothesis suggests why this may be so. Newman (ref. 7) modeled the plasticity-induced compressive stresses left by a propagating long crack as shown in figure 5. This figure shows that the greatest closure stresses occur in the immediate vicinity of the crack tip, with the closure stresses decreasing quickly in the crack wake behind the crack tip. Crack closure loads for both short and long cracks are similar due to the dominating effect of the highest closure stresses in the immediate vicinity of the crack tip. These high closure stresses result in the initial crack closure occurring at the crack tip during unloading. This initial closure of the crack tip determines ΔK_{eff}. The continued unloading results in a progressive crack closure further away from the crack tip. However this has no effect on ΔK_{eff} and FCG rates, since the crack tip is already closed. Thus a reduction of closure stresses behind the crack tip, as has been postulated to account for short crack behavior, affects the amount of closure behind the crack tip and not the more important closure stress at the crack tip. This reduction of compressive stresses in the wake of the crack can be accomplished by: (a) machining away the crack wake; (b) transition from low to high stress intensity; (c) limited wake of short cracks.

It should be pointed out, that the closure stresses behind the crack tip, do play a major role in controlling FCG rates in the case of high-low loading sequence or when overloads are applied. In these instances, the closure stresses behind the crack tip are controlling the ΔK_{eff} since they are higher than the closure stresses at the crack tip.

SUMMARY AND CONCLUSIONS

A test program was conducted to determine the influence of crack closure on FCG rates of short cracks as compared to long crack. Using the standard compact tension specimen, test procedures were devised to simulate the reduction of closure stresses in the crack wake behind the crack tip, as has been

proposed to occur in the case of short cracks. Based on the results obtained, the following conclusions were made:

(1) Crack closure does not appear to be the major reason for the accelerated growth of short cracks.

(2) It was proposed that crack closure stresses for both short and long cracks are similar due to the dominating effect of the highest closure stresses occurring in the immediate vicinity of the crack tip.

(3) The magnitude of the closure load was not affected by incrementally reducing the wake of the crack.

(4) When the ΔK in the specimen was dramatically increased, no variation in FCG rate was observed as a function of crack length after the transition point.

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TABLE I - TENSILE PROPERTIES - 7075-T6

Orientation	Ultimate strength		Yield strength		Elongation, percent
	MPa	ksi	MPa	ksi	
Longitudinal	565	82	524	76	12
Longitudinal transverse	579	84	517	75	13

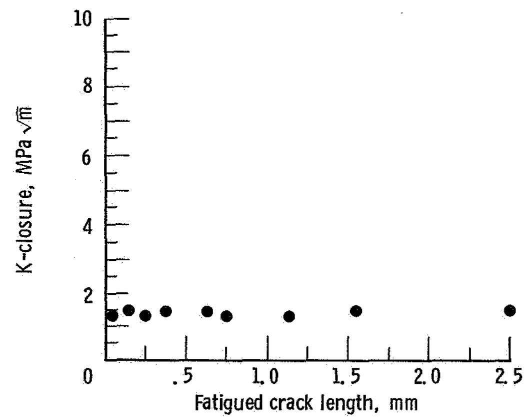


Figure 1. - Crack closure versus fatigued crack length.

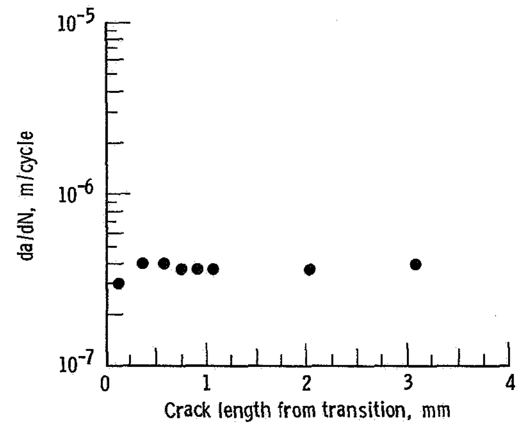


Figure 2. - FCG rate as a function of crack length after transition into higher ΔK.

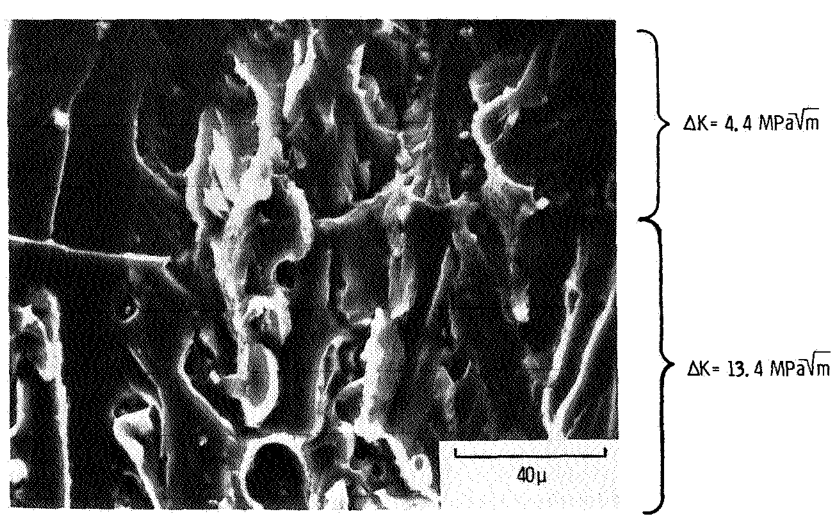
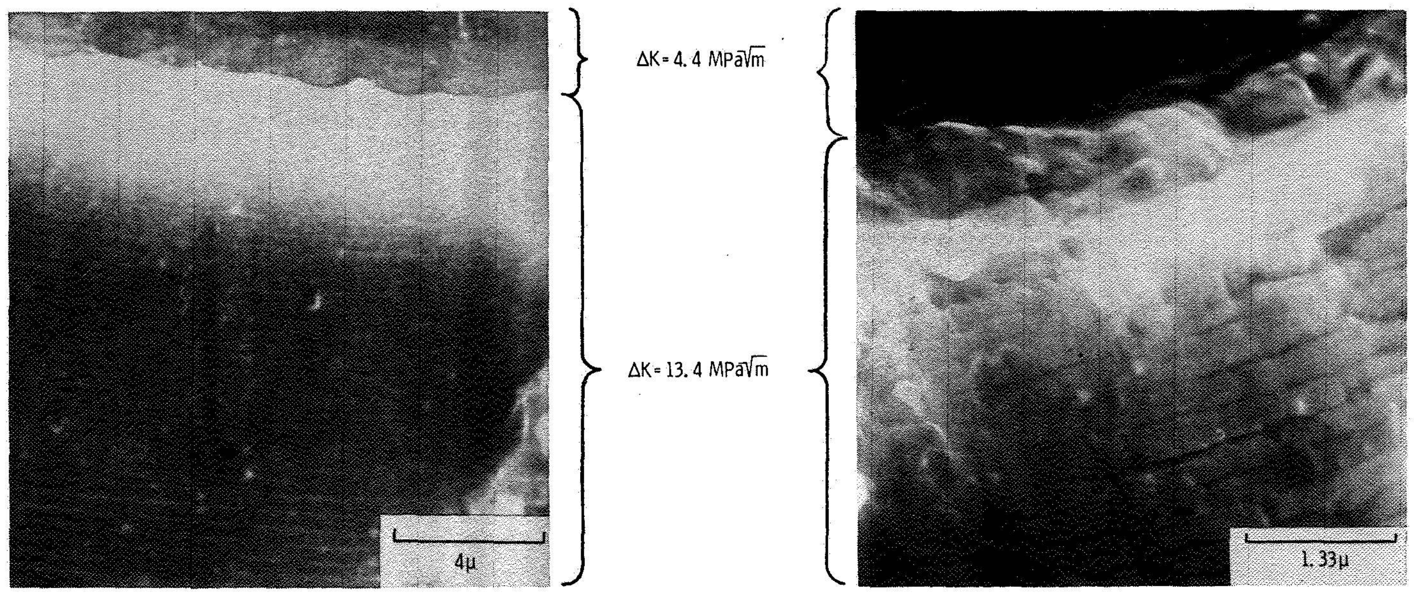


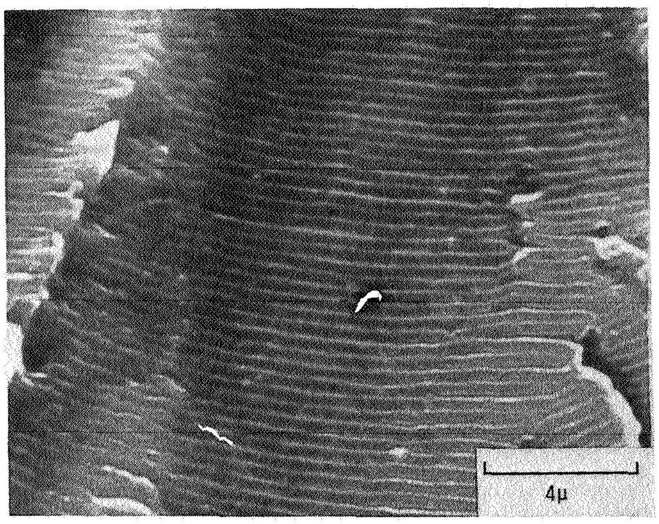
Figure 3. - Fractograph showing transition from low to high ΔK.



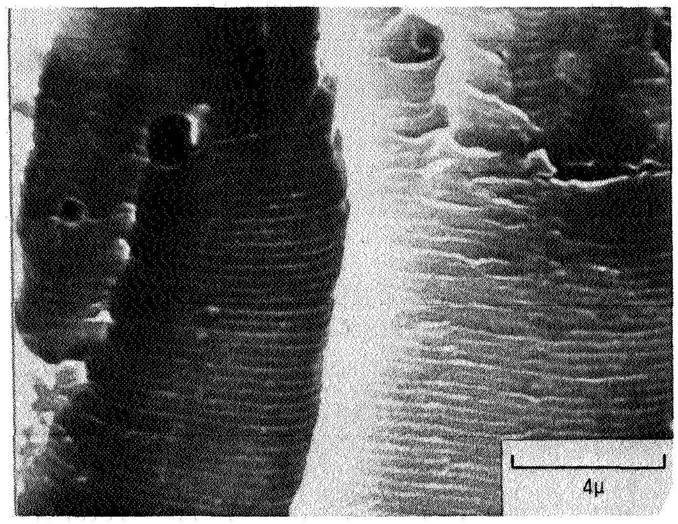
(a) $da/dn = 3.37 \times 10^{-7}$ m/cycle

(b) $da/dn = 3.05 \times 10^{-7}$ m/cycle

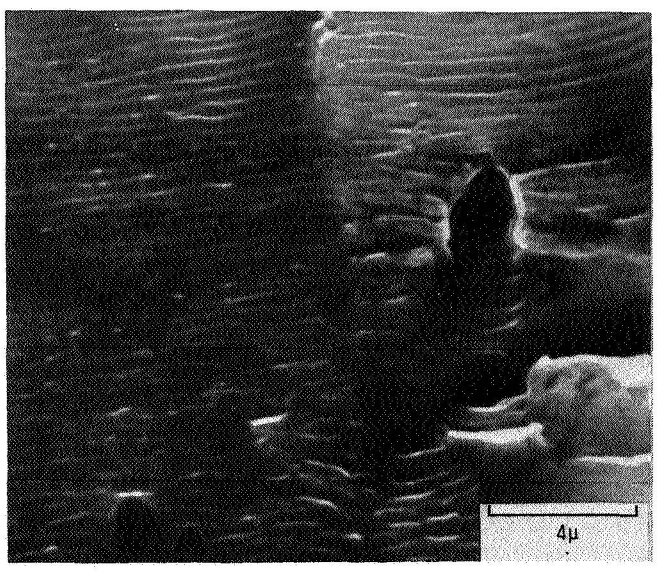
Figure 4. - Fractographs showing striation spacing after transition to high ΔK. All crack growth measurements obtained from striation spacings.



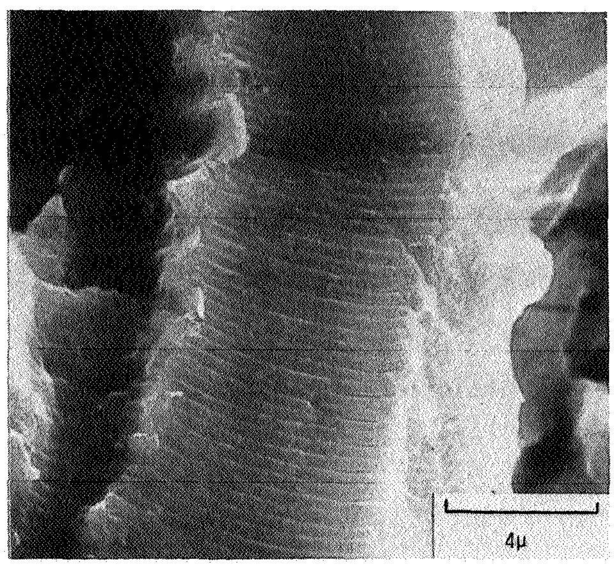
(c) da/dn = 3.26 x 10^{-7} m/cycle 50μ from transition.



(d) da/dn = 3.07 x 10^{-7} m/cycle 100μ from transition.



(e) da/dn = 3.6 x 10^{-7} m/cycle 150μ from transition.



(f) da/dn = 3.37 x 10^{-7} m/cycle 2500μ from transition.

Figure 4. - Concluded.

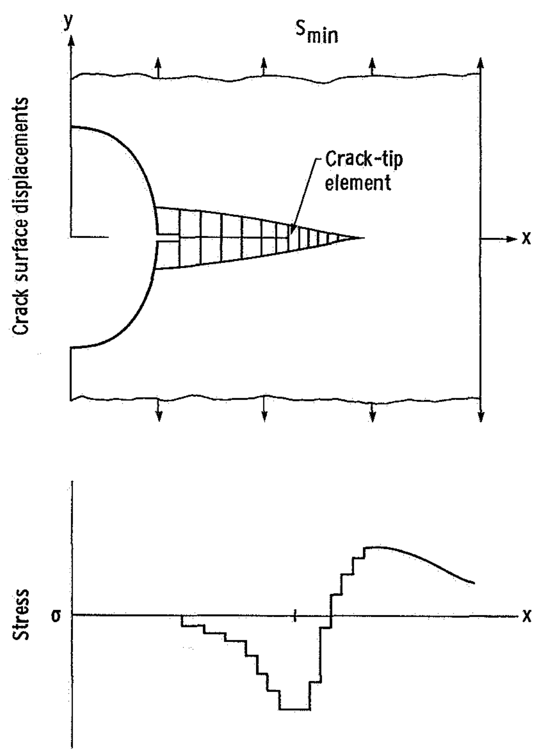


Figure 5. - Crack surface displacements and stress distributions along crack line at minimum stress (ref. 7).

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15. Supplementary Notes

16. Abstract

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